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CFD simulation of direct contact membrane distillation modules with rough surface channels

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Abstract

Membrane distillation (MD) can utilize low level thermal energy, such as waste heat and solar thermal heat, and holds high potential to replace conventional energetically intensive separation technologies. Two issues related to MD were investigated in this study by computational fluid dynamics (CFD) simulation. First, the trans-membrane mass fluxes are controlled by the heat transfer in the boundary layers adjacent to the membrane, but the applicability of conventional correlations developed for rigid heat exchangers on MD is questionable. Second, reported experimental study has shown that employing fluid channels with rough surface can enhance the performance of MD. However, the internal transfer characteristics of these modules have not been analyzed. This paper presents the results of the 3-D CFD simulation of the direct contact MD (DCMD) modules with and without rough surface channels for desalination. The simulation is comprehensive in that it covers the entire length of the module and takes into account the trans-membrane heat and mass transfer. The model was verified with reported experiment data and the average deviation of mass flux is less than 10%. The simulation results reveal that the thermal entrance effect, which gives very high mass flux and heat transfer coefficient, is significant for the simulated modules. The averaged heat transfer coefficients of the entire module are not close to the predictions from the conventional correlations. Hence, directly applying the conventional correlations of heat transfer coefficients to the MD modules is not appropriate.

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1. Introduction

Membrane distillation (MD) is a separation process in which only volatile species permeate through a porous hydrophobic membrane. MD can be carried out at low temperature by waste heat or solar thermal heat and shows great potential to replace conventional energetically intensive separation technologies.

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Direct contact membrane distillation (DCMD), in which the membrane is in direct contact with a hot liquid and a cold liquid, is the simplest MD configuration capable of producing reasonably high flux. It is best suited for applications such as desalination and concentration of aqueous solutions (e.g., juice concentrates) [1].

In MD, heat and mass transfers are coupled together in the same direction from the hot side to the cold side of the membrane. Besides the permeation inside the membrane, the mass transfer is determined by the vapor pressure difference across the membrane, which is controlled by the boundary layer heat transfer of both fluid channels. The design of MD processes calls for the boundary layer heat transfer coefficients. However, because of the mass transfer across the membrane boundary, the appropriateness of applying conventional correlations developed for rigid heat exchangers on the MD processes has been questioned [2]. However, no in-depth examination of this issue has been reported yet.

Roughened surface is a passive heat transfer enhancement method for heat exchangers. Ho et al. [3] applied rough surfaces on DCMD modules for desalination and their experimental study reported permeation flux improvement. However, the internal transfer characteristics of the modules have not been analyzed.

Computational fluid dynamics (CFD) is a power tool to rigorously simulate the transport phenomena in many systems. On the CFD study of MD, for representative segments of spacer-filled MD modules or the entire hollow-fiber MD modules, 2-D or 3-D CFD simulations of fluid flow and/or heat transfer were used to study different module designs [4-7]. In this study, a 3-D CFD simulation which is more comprehensive than that reported in the literature was employed to simulate the entire DCMD modules with and without rough surface channels for desalination. The simulation covered the entire length of the module and the model takes into account the trans-membrane heat and mass transfer. The purposes are to obtain the internal transfer profiles of the MD modules and to examine the applicability of conventional correlations of heat transfer coefficient to the MD modules.

2. Modeling

The CFD computation domain and grid of the DCMD module are shown in Fig. 1. The module is the same as the experimental module of [3]. As [3], channels with three levels of roughness operated under both counter-flow and co-flow configurations were studied. The rough surface was simulated with a uniform array of rectangular elements, as depicted in Fig. 2.

The laminar flow model of the FLUENT software was employed for the CFD simulation. The trans-membrane heat and mass fluxes were include in the model using the information of the cells adjacent to the membrane. The mechanisms of heat transfer (heat conduction) and mass transfer (Knudsen diffusion, molecular diffusion and viscous flow) were taken into account to calculate the fluxes. Grid independent analysis was carried out to determine the appropriate grid sizes. In addition to the conservations of momentum, energy and mass, the trans-membrane mass flux was included in the convergence criteria.

The model was verified with the experimental data reported in [3]. For all the modules with different roughness operated under experimental conditions, the average deviation of the model predicted from the experimental mass flux is less than 10%. The simulation and experimental data of the module average trans-membrane flux for the R44 channel module operated under different flow rates and hot fluid temperatures are shown in Fig. 3.

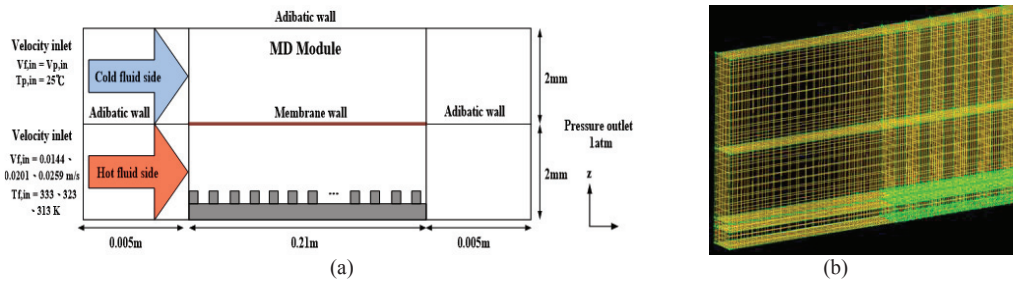


Fig. 1. DCMD module with rough surface in hot fluid channel (a) CFD computation domain; (b) grid

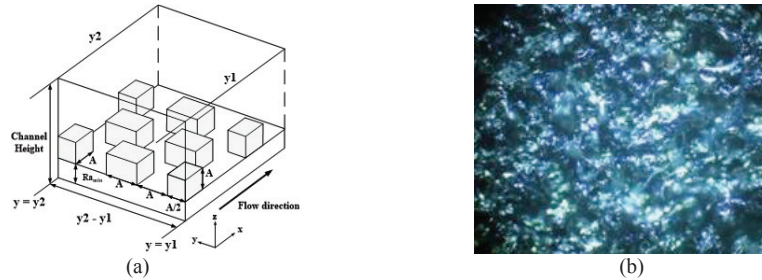


Fig. 2. Rough surface channel (a) simulated rough surface; (b) the rough surface used for experiment

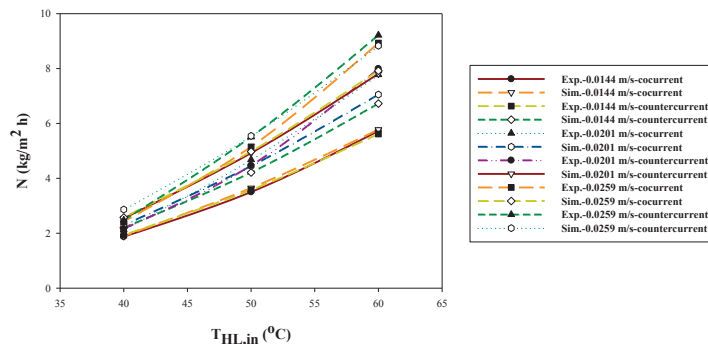


Fig. 3. Model verification (R44 channel module)

3. Results and discussion

The velocity profile in Fig. 4(a) for a co-flow base case T1V1R44 (R44 channel module operated under hot fluid of T1 temperature and V1 velocity) shows the valley-shape contour near the rough elements. The temperature profile in Fig. 4(b) shows that the bottom hot channel has a shorter thermal entrance length than the top cold channel due to the rough surface in the hot channel. The local trans-membrane mass flux profiles inside the modules are shown in Fig. 5. For the co-flow configuration, much higher flux at the inlet end is obtained due to the thermal entrance effect. For the counter-flow configuration, high-flux profiles are seen at both ends due to the thermal entrance effects at the two channels. In the figures, it is also observed that the channels with greater roughness give higher mass fluxes. The entrance effects also result in higher heat transfer coefficients for both co- and counter-flow configurations, as shown in Fig. 6(a). Furthermore, the counter-flow module gives higher heat transfer coefficients than the co-flow module. The channels with greater roughness offer higher heat transfer coefficients too. The effect of trans-membrane mass transfer on the heat transfer coefficient is summarized in Fig. 6(b). The effect is not significant.

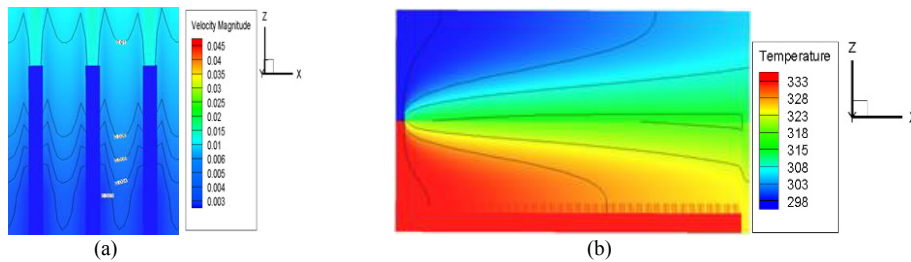


Fig. 4. Simulated profiles of T1V1R44 case (a) velocity contours near rough elements (b) temperature contours

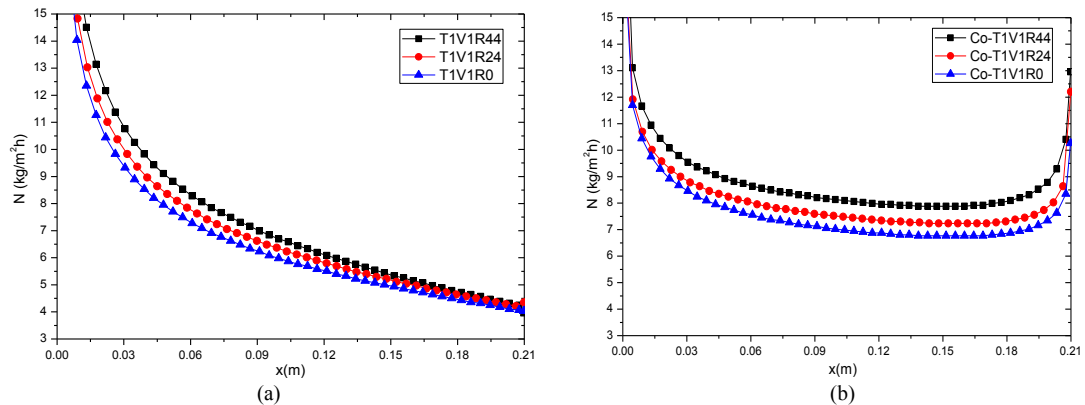


Fig. 5. Simulated local trans-membrane mass flux (a) co-flow; (b) counter-flow

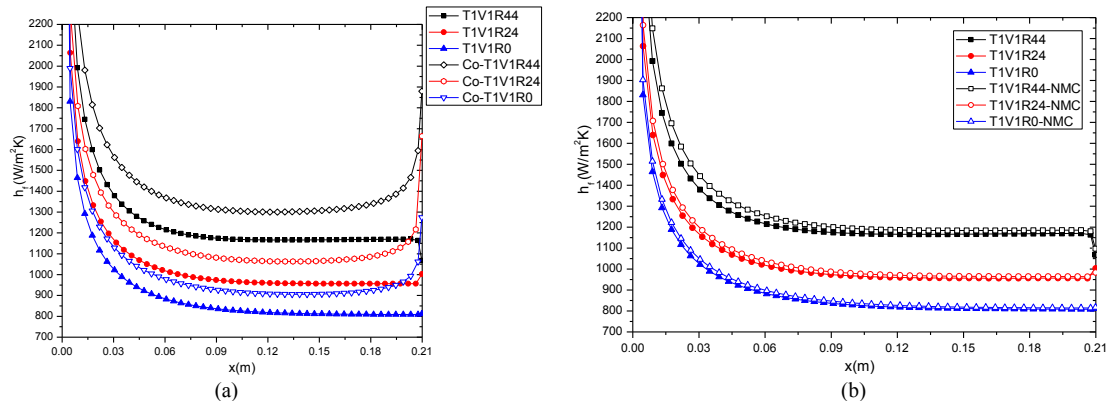


Fig. 6. Simulated local heat transfer coefficient of hot fluid channel (a) different configurations; (b) w/ and w/o (NMC) trans-membrane mass transfer

The simulation results are compared to the conventional correlations developed for rigid heat exchangers, which do not involve mass transfer across the boundary. First, because the entrance effect is significant in the MD modules, as shown in the previous figures, the thermal entrance lengths obtained from the CFD simulation are compared to the Shah and London correlation [8] in Fig. 7. The results are fairly close in the hot channel, but the simulation results are lower than the correlation predictions in the cold channel.

The comparison of local heat transfer coefficient in the hot channel with greatest roughness, R44, to the correlations listed in Table 1 is shown in Fig. 8. The correlations applicable to the entrance region, no. [4] to no. [6], are not close to the simulation results. Excluding the entrance region, the simulation results are most close to the correlation no. [2]. The averaged heat transfer coefficients of the entire module from the CFD simulation are compared to the correlations in Fig. 9. For the co-flow configuration, the simulation results fall between the predictions from correlations no. [7] and no. [2]. For the counter-flow configuration, the simulation results are close to the prediction from correlation no. [7], which is for hydrodynamic and thermal simultaneously developing flow.

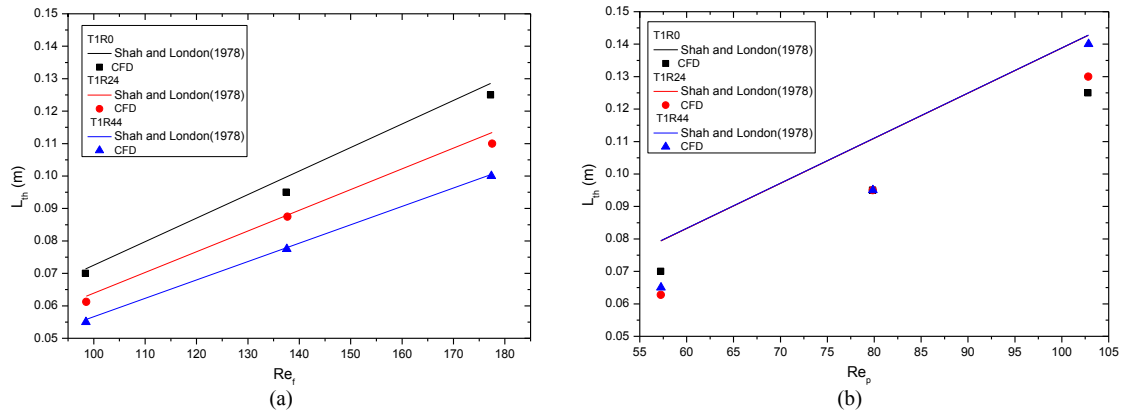


Fig. 7. Comparison of CFD simulated thermal entrance length with correlation (a) hot channel; (b) cold channel

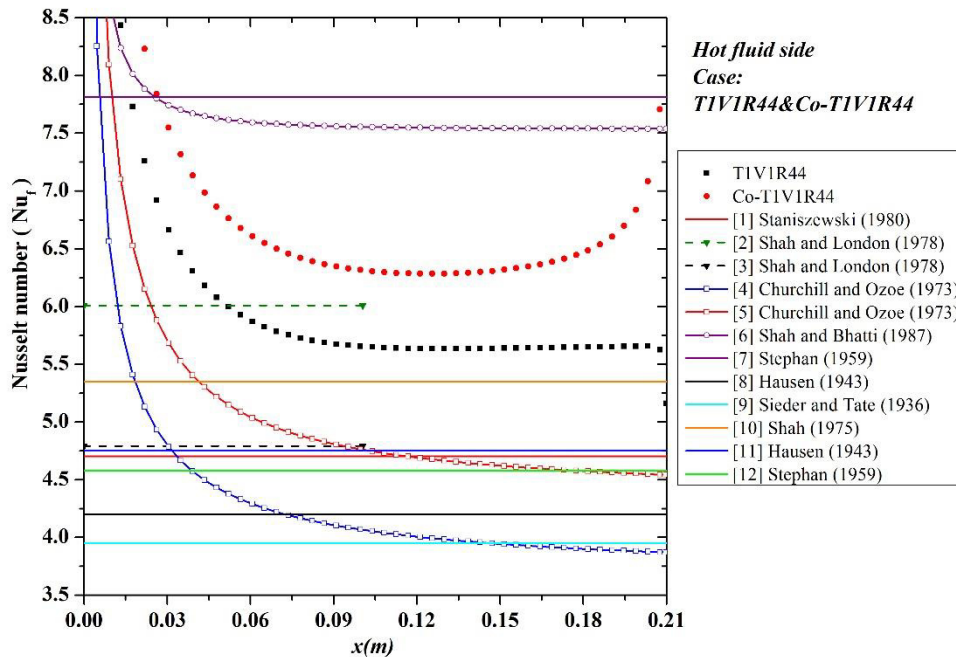


Fig. 8. Comparison of local heat transfer coefficients with correlations (co-flow (TIV1R44) and counter-flow (co-TIV1R44) cases)

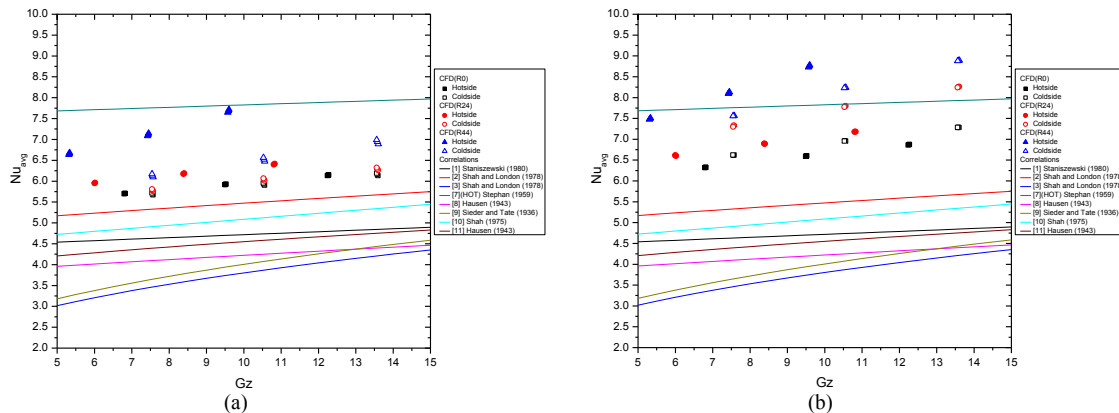


Fig. 9. Comparison of averaged heat transfer coefficients with correlations (a) co-flow; (b) counter-flow

Table 1. The correlations of heat transfer coefficient

No.	Correlation	Applicable conditions	References
[1]	$Nu_m = 4.36 + \frac{0.036 (RePrD_h/L)}{1 + 0.0011 \left(\frac{RePrD_h}{L} \right)^{0.8}}$	• FDF • UWF • Circular tube	Stanislawski (1980) Kakac (1983)
[2]	$Nu_m = 4.86 + \frac{0.06063 \left(\frac{RePrD_h}{L} \right)^{1.2}}{1 + 0.09094 \left(\frac{RePrD_h}{L} \right)^{0.7} Pr^{0.17}}$	• SDF • HDF+TDF • UWT • Parallel plate channel with one surface insulated	Shah and London (1978)
[3]	$Nu_m = 1.765 \left(\frac{RePrD_h}{L} \right)^{0.333}$	• UWT • TDF • Rectangular channel	Shah and London (1978)
[4]	$\frac{Nu_z + 1.7}{5.357[1 + (Gz/97)^{8/9}]^{3/8}} = \frac{Gz/71}{[1 + (Pr/0.0468)^{2/3}]^{1/2} [1 + (Gz/97)^{8/9}]^{3/4}}^{4/3}^{3/8}$	• Local Nu number • SDF • TDF+TDF • UWT • Circular duct	Churchill and Ozoe (1973)
[5]	$\frac{Nu_z + 1}{5.364[1 + (Gz/55)^{10/3}]^{3/10}} = \frac{Gz/28.8}{[1 + (Pr/0.0207)^{2/3}]^{1/2} [1 + (Gz/55)^{10/9}]^{3/5}}^{5/3}^{3/10}$	• Local Nu number • SDF • TDF+TDF • UWF • Circular duct	Churchill and Ozoe (1973)
[6]	$Nu_{z,T} = 7.55 + \frac{0.024(z^*)^{-1.14} (0.0179Pr^{0.17}(z^*)^{-0.64} - 0.14)}{(1 + 0.0358Pr^{0.17}(z^*)^{-0.64})^2}$	• Local Nu number • UWT • SDF • Parallel plate channel • $0.1 \leq Pr \leq 1000$	Shah and Bhatti (1987)
[7]	$Nu_m = 7.55 + \frac{0.024(z^*)^{-1.14}}{1 + 0.0358(z^*)^{-0.64}Pr^{0.17}}, \quad 0.1 < Pr < 1000$	• UWT • SDF • Parallel plate channel	Stephan (1959)
[8]	$Nu_m = 3.66 + \frac{0.0668 \left(\frac{D_h}{L} \right) RePr}{1 + 0.04 \left[RePr \left(\frac{D_h}{L} \right) \right]^2}$	• UWT • TDF+TDF • Circular tube	Hausen (1943)
[9]	$Nu_m = 1.86 \left(\frac{RePrD_h}{L} \right)^{\frac{1}{3}} \left(\frac{\mu}{\mu_w} \right)^{0.14}$	• UWT • FDF • Circular tube	Sieder and Tate (1936)
[10]	$Nu_m = \begin{cases} 1.953 \left(RePr \frac{D_h}{L} \right)^{\frac{1}{3}}, & RePr \frac{D_h}{L} \geq 33.3 \\ 4.364 + 0.0722 \left(RePr \frac{D_h}{L} \right), & RePr \frac{D_h}{L} < 33.3 \end{cases}$	• FDF • UWF • Circular tube	Shah (1975)
[11]	$Nu_m = 3.657 + \frac{0.19 \left(RePr \frac{D_h}{L} \right)^{0.8}}{1 + 0.117 \left[RePr \left(\frac{D_h}{L} \right) \right]^{0.467}}$	• FDF • UWT • Circular tube	Hausen (1943)
[12]	$Nu_m = 3.657 + \frac{0.0677 \left(RePr \frac{D_h}{L} \right)^{1.33}}{1 + 0.1Pr \left(RePr \frac{D_h}{L} \right)^{0.3}}$	• FDF • UWT • Circular tube	Stephan (1959)

FDF: Fully developed flow, HDF: Hydrodynamic developing flow, SDF: Hydrodynamic and thermal simultaneously developing flow, TDF: Thermal developing flow, UWF: Uniform wall flux, UWT: Uniform wall temperature.

For heat transfer enhancement using rough surface, the relative increase of heat transfer to friction loss can be evaluated using a thermohydraulic performance parameter [9]:

$$\eta_{\text{THPP}} = (\text{Nu}_r/\text{Nu}_s)/(\text{f}_r/\text{f}_s)^{1/3} \quad (1)$$

The results of η_{THPP} are shown in Fig. 10. The parameter values are higher for the R44 channel, which has greater roughness. The parameter values increase linearly with Reynolds number for counter-flow configuration, but stay constant or slightly increase with Reynolds number for co-flow configuration.

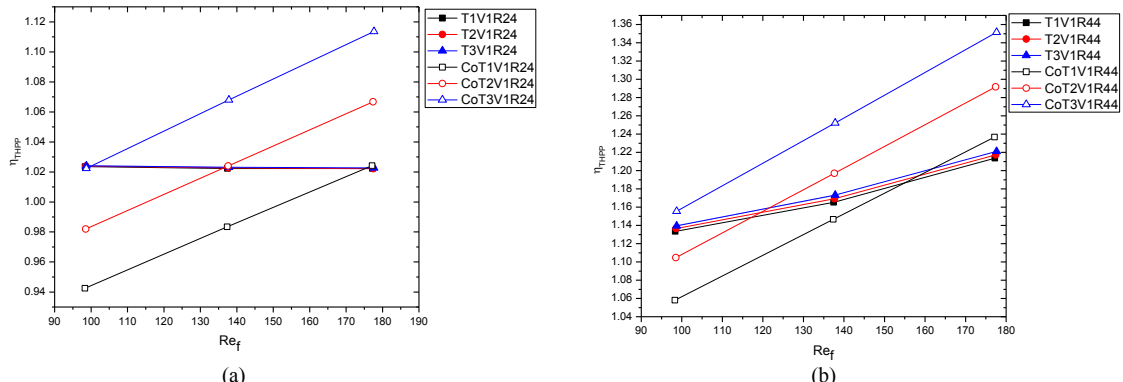


Fig. 10. Thermohydraulic performance parameter (a) R24 channel; (b) R44 channel

4. Conclusions

The 3-D CFD simulation results of the internal transfer characteristics of DCMD modules with and without rough surface channels for desalination have been presented. The comprehensive model includes the trans-membrane heat and mass transfer and the entire length of the module was simulated.

This simulation study has clarified and confirmed the following points:

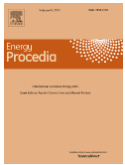
- (1) The simulated rough surface employed in this study gives close predictions to the experimental results.
- (2) In view of the significant variations of temperature and transfer fluxes along the length of the MD modules, the simulation of the entire module, rather than a presumed representative section of the module, is necessary.
- (3) For MD modules operated with fluid flow rates much higher than the trans-membrane mass fluxes, as long as the trans-membrane heat flux includes the phase change heat effect associated with the mass flux, the exclusion of trans-membrane mass flux in the model is acceptable. However, if the fluid flow rates are low, the inclusion of trans-membrane mass flux in the model is necessary.
- (4) The thermal entrance effects in the MD modules are significant and cannot be neglected.
- (5) The use of conventional correlations developed for rigid heat exchangers for estimating the average heat transfer coefficient of the entire MD module cannot be justified.

Acknowledgements

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Biography

Hsuan Chang is a professor in the Department of Chemical and Materials Engineering, Tamkang University, Taiwan. She received her Ph.D. from the Department of Chemical Engineering of Ohio State University, USA. Her research interest is in the simulation and design of chemical and energy processes.